

# Control of spin coherence in $n$ -type GaAs quantum wells using strain

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We show that the bulk-inversion-asymmetry-type strain-induced spin-orbit coupling can be used to effectively modify the Dresselhaus spin splitting in (001) GaAs quantum wells with small well width and the resulting spin dephasing time can be increased by two orders of magnitude to nanoseconds under right conditions. The efficiency of this strain manipulation of the spin dephasing time under different conditions such as temperature, electric field and electron density is investigated in detail.

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Manipulation of the spin coherence/dephasing in Zinc-blend semiconductors, where the symmetry of the spin degrees of freedom is broken due to the lack of inversion center of the crystal, is one of the fundamental subjects in semiconductor spintronics<sup>1,2,3</sup> which aims to incorporate the spin degrees of freedom into the traditional electronic devices. It has been shown both experimentally and theoretically that many effects, such as magnetic field and electric field, can strongly affect the spin precession and spin dephasing.<sup>4,5,6,7,8,9</sup> Very recently strain has also been shown to be effective in spin manipulation. Kato *et al.* reported experimentally that strained bulk semiconductors exhibit spin splitting in the presence of applied electric fields.<sup>10</sup> They further used this strain-induced spin splitting to generate spin polarization in the presence of an electric current.<sup>11</sup> In this report we demonstrate that strain can also be used to effectively control the spin coherence and greatly enhance the spin dephasing time (SDT).

The leading spin dephasing mechanism in  $n$ -type GaAs quantum well (QW) in the absence of applied electric field along the growth direction is the D'yakonov-Perel' mechanism<sup>12</sup> due to the Dresselhaus<sup>13</sup> spin splitting  $\mathbf{h}(\mathbf{k}) \cdot \boldsymbol{\sigma}/2$ .<sup>14,15</sup> In (001) QW with the growth direction along the  $z$ -axis,  $\mathbf{h}(\mathbf{k})$  contains terms both linear and cubic in  $k$ . When only the lowest subband is populated, it reads  $h_x(\mathbf{k}) = -\gamma k_x(\langle k_z^2 \rangle - k_y^2)$ ,  $h_y(\mathbf{k}) = \gamma k_y(\langle k_z^2 \rangle - k_x^2)$  and  $h_z(\mathbf{k}) = 0$  with  $\gamma$  denoting the spin-orbit coupling strength<sup>16</sup> and  $\langle k_z^2 \rangle$  representing the average of the operator  $-(\partial/\partial z)^2$  over the electronic state of the lowest subband. Under the infinite-well-depth assumption,  $\langle k_z^2 \rangle = (\pi/a)^2$  with  $a$  standing for the well width. It has been shown very recently<sup>9</sup> from a full many-body kinetic study of the spin dephasing that for narrow well width with  $\pi^2/a^2 \gg \langle k_x^2 \rangle$  and  $\pi^2/a^2 \gg \langle k_y^2 \rangle$ , the linear term in  $\mathbf{h}(\mathbf{k})$  is dominant and the SDT *increases* with temperature. Here  $\langle \dots \rangle$  stands for the average subject to the Fermi distribution. However, when the well width is big enough and/or the temperature is high enough that the cubic term is dominant, the SDT decreases with temperature as commonly expected.<sup>9</sup>

Strain introduces additional spin splittings and the leading one is the one of bulk-inversion-asymmetry type:<sup>17</sup>  $h_x^s(\mathbf{k}) = -Dk_x(\epsilon_{yy} - \epsilon_{zz})$ ,  $h_y^s(\mathbf{k}) = -Dk_y(\epsilon_{zz} -$

$\epsilon_{xx})$ ,  $h_z^s(\mathbf{k}) = -Dk_z(\epsilon_{xx} - \epsilon_{yy})$ , and is linear in  $k$ .  $D$  is the material constant. Therefore the linear term of the Dresselhaus spin splitting  $\mathbf{h}(\mathbf{k})$  can be adjusted by the strain and the total spin splitting term can be written as  $\mathbf{h}^t(\mathbf{k}) \cdot \boldsymbol{\sigma}/2$  with

$$h_x^t(\mathbf{k}) = [(-\alpha + \beta) + \gamma k_y^2]k_x, \quad (1)$$

$$h_y^t(\mathbf{k}) = -[(-\alpha + \beta) + \gamma k_x^2]k_y, \quad (2)$$

and  $h_z^t(\mathbf{k}) = 0$  by taking the strain  $\epsilon_{xx} = \epsilon_{yy}$  and  $\epsilon_{zz} - \epsilon_{xx} > 0$ .<sup>10,11</sup>  $\alpha = \gamma(\pi/a)^2$  and  $\beta = D\epsilon$  with  $\epsilon = \epsilon_{zz} - \epsilon_{xx}$ . Equations (1) and (2) clearly indicate that under certain well width and strain,  $\alpha = \beta$  and the spin splitting can be totally determined by the cubic term. In addition, by modulating the magnitude of the strain, the relative magnitudes of the linear and cubic terms are varied. Different dependences of the SDT on the external conditions such as temperature, electric field and electron density are therefore expected under different strains. Finally one may dramatically suppress the spin dephasing by adjusting the strain to satisfy the condition  $\alpha - \beta = \gamma \langle k_\xi^2 \rangle$  with  $\xi = x, y$ .

We construct the many-body kinetic spin Bloch equations<sup>18</sup> by the non-equilibrium Green function method<sup>19</sup> as follows:<sup>8</sup>

$$\dot{\rho}_{\mathbf{k},\sigma\sigma'} - e\mathbf{E} \cdot \nabla_{\mathbf{k}} \rho_{\mathbf{k},\sigma\sigma'} = \dot{\rho}_{\mathbf{k},\sigma\sigma'}|_{\text{coh}} + \dot{\rho}_{\mathbf{k},\sigma\sigma'}|_{\text{scatt}} \quad (3)$$

with  $\rho_{\mathbf{k},\sigma\sigma'}$  representing the single-particle density matrix elements. The diagonal elements  $\rho_{\mathbf{k},\sigma\sigma} \equiv f_{\mathbf{k},\sigma}$  describe the electron distribution functions of wavevector  $\mathbf{k}$  and spin  $\sigma$  ( $= \pm 1/2$ ). The off-diagonal elements  $\rho_{\mathbf{k},\frac{1}{2}-\frac{1}{2}} = \rho_{\mathbf{k},-\frac{1}{2}\frac{1}{2}}^* \equiv \rho_{\mathbf{k}}$  describe the inter-spin-band correlations for the spin coherence. The second term in the kinetic equations describes the momentum and energy input from a uniform external electric field  $\mathbf{E}$  along the  $x$ -axis.  $\dot{\rho}_{\mathbf{k},\sigma\sigma'}|_{\text{coh}}$  on the right hand side of the equations describes the coherent spin precession around the applied magnetic field  $\mathbf{B}$  (along the  $x$ -axis, *i.e.*, in the Voigt configuration), the effective magnetic field  $\mathbf{h}^t(\mathbf{k})$  as well as the effective magnetic field from the electron-electron interaction in the Hartree-Fock approximation:

$$\left. \frac{\partial f_{\mathbf{k},\sigma}}{\partial t} \right|_{\text{coh}} = -2\sigma \{ [g\mu_B B + h_x^t(\mathbf{k})] \text{Im}\rho_{\mathbf{k}} + h_y^t(\mathbf{k}) \text{Re}\rho_{\mathbf{k}} \} + 4\sigma \text{Im} \sum_{\mathbf{q}} V_{\mathbf{q}} \rho_{\mathbf{k}+\mathbf{q}}^* \rho_{\mathbf{k}}, \quad (4)$$

$$\begin{aligned} \left. \frac{\partial \rho_{\mathbf{k}}}{\partial t} \right|_{\text{coh}} &= \frac{1}{2} [ig\mu_B B + ih_x^t(\mathbf{k}) + h_y^t(\mathbf{k})] (f_{\mathbf{k}\frac{1}{2}} - f_{\mathbf{k}-\frac{1}{2}}) \\ &+ i \sum_{\mathbf{q}} V_{\mathbf{q}} [(f_{\mathbf{k}+\mathbf{q}\frac{1}{2}} - f_{\mathbf{k}+\mathbf{q}-\frac{1}{2}}) \rho_{\mathbf{k}} - \rho_{\mathbf{k}+\mathbf{q}} (f_{\mathbf{k}\frac{1}{2}} - f_{\mathbf{k}-\frac{1}{2}})] . \end{aligned} \quad (5)$$

$\dot{\rho}_{\mathbf{k},\sigma\sigma'}|_{\text{scatt}}$  denotes the electron-electron, electron-phonon and electron-impurity scattering. The expressions of these terms can be found in Ref. 8. One notices that all the unknowns appear in the scattering terms. Therefore the kinetic Bloch equations (3) have to be solved self-consistently to obtain the temporal evolution of the electron distribution functions  $f_{\mathbf{k},\sigma}(t)$  and the spin coherence  $\rho_{\mathbf{k}}(t)$ . The details of the calculation are laid out in Ref. 8. The SDT is obtained by the slope of the envelop of the incoherently summed spin coherence  $\rho = \sum_{\mathbf{k}} |\rho_{\mathbf{k}}(t)|$ .<sup>18,19,20</sup> It is understood that both true dissipation and the interference of many  $\mathbf{k}$  states may contribute to the decay. The incoherent summation is therefore used to isolate the irreversible decay from the decay caused by interference.<sup>19,20</sup>

We include the electron-longitudinal optical phonon and the electron-electron Coulomb scattering in the calculation. The impurity density is taken to be zero throughout the paper. The main results of our calculation are summarized in Figs. 1 to 4. In the calculation the material parameters are listed in Ref. 8. The width of the QW is fixed to be 10 nm. The material constant  $D$  is chosen to be  $D = 1.59 \times 10^4$  m/s following the experiment.<sup>10</sup>

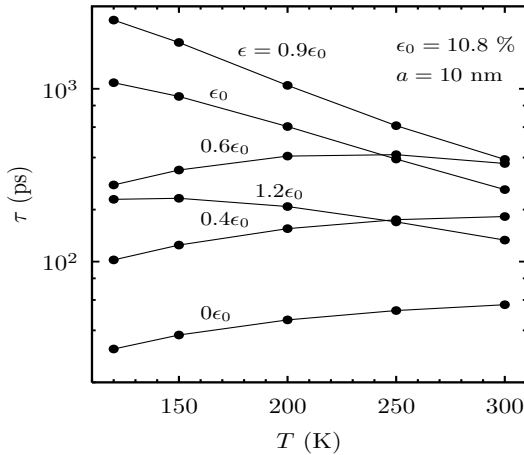


FIG. 1: SDT *vs.* the background temperature  $T$  under different strains. The electron density is  $4 \times 10^{11} \text{ cm}^{-2}$ .

First we investigate the temperature dependence of the

spin dephasing under different strains. The SDT versus the background temperature without an applied electric field is plotted in Fig. 1. It shows that the temperature dependence of the SDT under different strains is quite different. For small strain, say the strain is smaller than  $0.4\epsilon_0$  ( $\epsilon_0 \equiv \alpha/D$  denotes the strain at which the linear term in  $\mathbf{h}^t$  is exactly eliminated), the linear term in  $\mathbf{h}^t(\mathbf{k})$  is dominant and the SDT *increases* monotonously with the temperature. For strain around  $\epsilon_0$ , the contribution from the cubic term becomes important (or is the only  $\mathbf{k}$ -dependent term at  $\epsilon = \epsilon_0$ ), the SDT either first increases then decreases with  $T$  when there is still linear term contribution or decreases with  $T$  monotonically when there is no linear term left ( $\epsilon = \epsilon_0$ ).

These behaviors can be understood as follows:<sup>9</sup> When the temperature increases, the electron-electron and electron-phonon scattering is enhanced. Consequently electrons are driven to a more homogeneous state in  $\mathbf{k}$ -space. This tends to increase the SDT. In the meantime, the increase of temperature also drives electrons to a higher  $k$ -state and thus induces a larger  $h^t(\mathbf{k})$ . This tends to reduce the SDT. Both linear and cubic terms of  $h^t(\mathbf{k})$  increase with  $k$ , but with a different increase rate. When the linear term is dominant (*i.e.*,  $|\alpha - \beta| > \gamma \langle k_{\xi}^2 \rangle$ ), although its effect increases with temperature, the increase rate is slower than that of the scattering and the SDT increases with temperature. However, when the cubic term is dominant, the effect of the cubic term increases much faster with temperature than the scattering and the SDT decreases with the temperature. This effect is consistent with what obtained from strain-free QW's.<sup>9</sup>

From Fig. 1 one also notices that when the strain is applied, the SDT can be greatly enhanced. At low temperature it can be as long as *nanosecond* which is two orders of magnitude larger than the strain-free case. In order to show the strain dependence of the SDT, we plot in Fig. 2 the SDT as a function of strain for different temperatures. It is seen from the figure that the SDT first increases with strain until it reaches a maximum and then decreases with it. It is again noted that at low temperature (120 K) the varying range of the SDT versus  $\epsilon$  sweeps over two orders of magnitude with the maximum SDT being 2.5 ns. It is known that for QW with small width, the SDT is in the order of tens of picoseconds. The present results indicate the possibility of

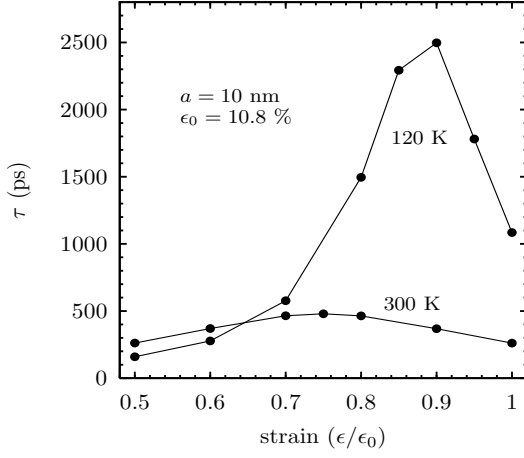


FIG. 2: SDT *vs.* strain at two temperatures. The electron density is  $4 \times 10^{11} \text{ cm}^{-2}$ .

using strain to obtain a very long SDT in GaAs QW's.

The physics of the  $\tau$ - $\epsilon$  dependence can be understood as following: For QW with  $a = 10 \text{ nm}$ ,  $\alpha = 1.72 \times 10^3 \text{ m/s}$ . When  $T = 120 \text{ K}$  and electron density is  $4 \times 10^{11} \text{ cm}^{-2}$ ,  $\gamma\langle k_x^2 \rangle = \gamma\langle k_y^2 \rangle = 2.21 \times 10^2 \text{ m/s}$ . Therefore for strain-free case ( $\beta = 0$ ) the linear term in Eqs. (1) and (2) is one order of magnitude larger than the cubic term. Introducing a positive strain reduces the linear term, at certain strain  $\gamma\langle k_x^2 \rangle - (\alpha - \beta) = 0$  and  $h^t(\mathbf{k})$  is greatly suppressed. Therefore one obtains a very large SDT.  $\epsilon$  predicted from above equation at 120 K (300 K) is  $0.87\epsilon_0$  ( $0.74\epsilon_0$  as  $\gamma\langle k_x^2 \rangle = 4.53 \times 10^2 \text{ m/s}$  at 300 K), which is in good agreement with  $0.9\epsilon_0$  ( $0.75\epsilon_0$ ) in Fig. 2.

Next we turn to the problem of the applied-electric-field dependence of the SDT under different strains. In Fig. 3(a), the SDT is plotted against the applied electric field  $E$ . It is noted that when the electron field is larger than  $500 \text{ V/cm}$ , hot-electron effect<sup>21</sup> starts to play an important role.<sup>8</sup> It is seen from the figure that the  $\tau$ - $E$  dependence is similar to the  $\tau$ - $T$  dependence. Figure 3(b) shows the strain dependence of the SDT under different electric fields. Again, one observes a peak under certain strain. These behaviors are understood as the electric field also affects the spin dephasing in two competing ways: On one hand, it drives the electrons to higher momentum states; On the other hand, it raises the hot-electron temperature and therefore the scattering is strengthened.

Finally, as  $\langle k_\xi^2 \rangle$  depends not only on temperature, but also on electron density, we show the strain dependence of the SDT at different electron densities. The external electric field is assumed to be zero. The result is summarized in Fig. 4. One finds that the  $\tau$ - $\epsilon$  dependence also shows a peak for each electron density. Moreover, the peak moves towards small strain when the electron density increases. This is in consistent with the fact that  $\langle k_\xi^2 \rangle$  increases with the electron density.

In conclusion, we have studied the effect of strain on

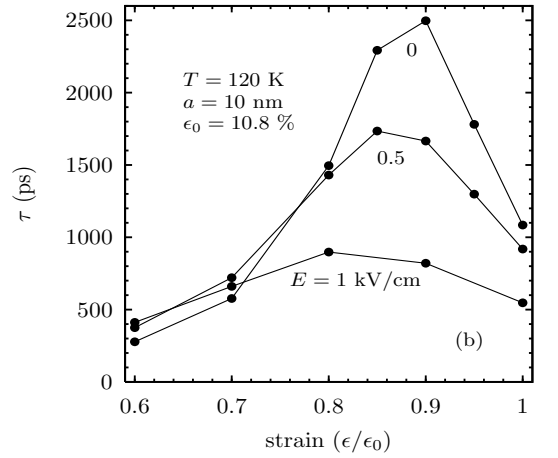
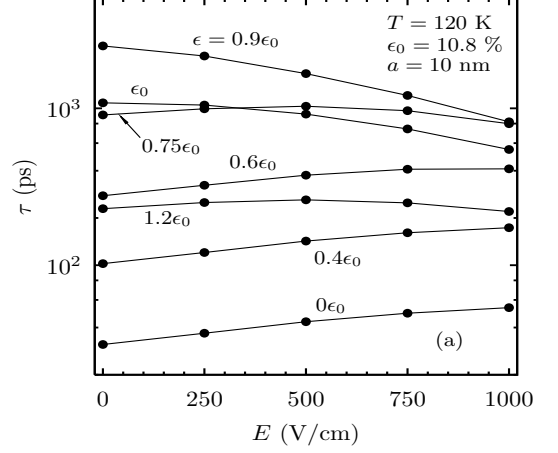


FIG. 3: Electron field dependence of the SDT. SDT *vs.* the applied electric field  $E$  under different strains (a) and the strain  $\epsilon$  at different electric fields (b). The electron density is  $4 \times 10^{11} \text{ cm}^{-2}$ .

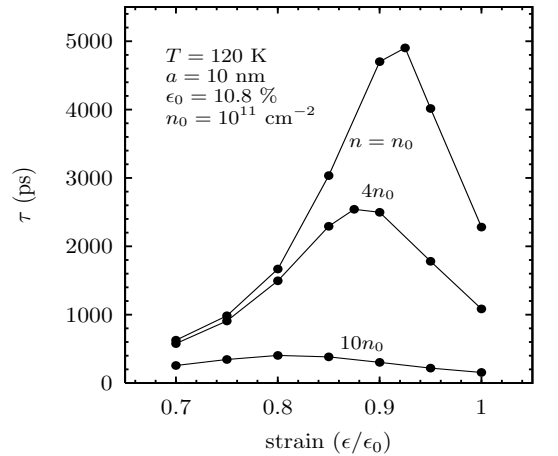


FIG. 4: SDT *vs.* the strains at different electron densities.  $T = 120 \text{ K}$ .

the spin dephasing in (001) GaAs QW's with a small well width under different conditions such as temperature, electric field and electron density. We show that one can effectively adjust the Dresselhaus spin splitting via strain in two dimension case. Especially at certain conditions the Dresselhaus spin splitting can be mostly canceled by the strain and one may get an *extremely* long SDT (up to nanoseconds in comparison to tens of picoseconds in

ordinary strain-free sample) in narrow GaAs QW's. This provides a unique way to control the spin coherence and get two-dimensional devices with extremely long SDT.

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